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(Article begins on next page)

Composable Battery Model Templates Based on Manufacturers' Data

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***Abstract*—Battery modeling has become a fundamental support in the design of electronic systems. Although the portfolio of battery models is extremely vast, there is an intrinsic weakness in the construction of these models. In most cases the information available in datasheets is insufficient to identify the model parameters; thus, designers must resort to measurements for that purpose.**

This paper describes a methodology that reverses the paradigm: starting from the available manufacturer data, the designer is provided with a systematic method to populate the best possible model allowed by the information at hand, through a modular and composable circuit-equivalent model template.

***Index Terms*—Li-ion battery, battery modeling, model identification, datasheet, equivalent circuit, analytical model.**

I. Introduction

Modeling of batteries shifted from a niche topic mainly of interest to battery manufacturers to a wide-ranging discipline to which researchers belonging to different communities contribute. This is mainly due to the increased diffusion of battery-powered appliances in many diverse application domains.

In this context, electronic designers favor models in which the battery dynamics is mimicked by an equivalent electrical circuit [1], because it can be easily incorporated into existing EDA tools and co-simulated with the rest of the system. However, the many circuit-equivalent models found in the literature share a common feature that makes them unwieldy: the identification of the model parameters (e.g., values of circuit elements) requires information that in most cases are not available in datasheets, thus requiring costly and time consuming measurements.

Although some recent works have proposed strategies to build circuit-equivalent battery models from manufacturers' data [2], they do not address the real challenge: **the actual structure of the model depends on what data are available**.

In this work, we propose a methodology to address this issue by reverting the classical paradigm: rather than deciding a model upfront and identify its parameters, we start from a battery datasheet and define a model that can be built from the available information.

The distinctive feature of this methodology is the use of a **composable model template** in the form of an electrical circuit, which is populated according to the manufacturer's data. In this way, even a datasheet with only a minimal amount of data makes it possible to build a circuit equivalent, albeit simpler and less accurate.

II. Background

A. Battery Non-Idealities

A battery is often considered an ideal voltage source, but it is indeed a complex electro-chemical device involving complicated chemical reactions resulting in various non-idealities. These can be categorized into first-order effects related to working conditions (i.e., battery charge/discharge patterns), and second-order effects related to operating conditions (e.g., temperature). This work is concerned with the modeling of the former type of effects.

The most relevant non-ideality is the *rated capacity* effect [3], i.e., the fact that the usable capacity of a battery depends on the magnitude of the discharge current: at higher currents, a battery is less efficient in converting its chemically stored energy into electrical energy, as shown in Fig. 1.

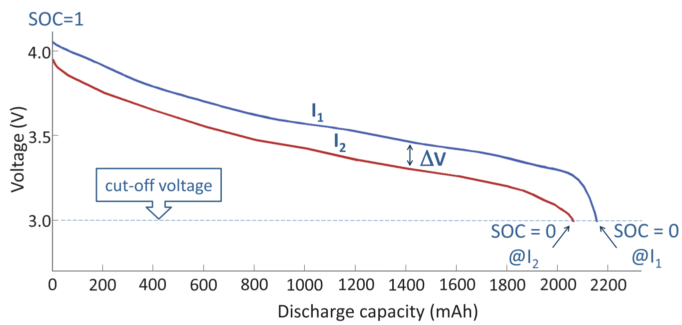


Fig. 1. Rated capacity effect of a battery at different discharge currents.

In practice, a battery starting from a full state-of-charge (SOC) always reaches the cutoff voltage after a 100% depth-of-discharge (DOD); nevertheless, the total energy provided during a cycle depends on the discharge characteristics.

B. Battery Models

Battery models fall into three main categories: *electrochemical*, *analytical* and *circuit-based* models. Electrochemical models are based on the internal chemical process modeling and analysis [4]. They are very accurate and virtually every aspect of the behavior can be estimated. However, their use is quite unfriendly for an electronic designer with little knowledge of the electro-chemical characteristics of the battery.

Analytical models describe the battery with one or more empirically-derived equations that relate relevant figures of merit to some battery, load, or environmental parameters. Peukert's law is the most popular model to estimate battery lifetime related to the discharging current [5]. It models the non-linear dependency between battery capacity and the discharge current as $t = \frac{C_p}{I^k}$, where C_p, known as "Peukert Capacity", corresponds to the capacity of a battery discharged at $I = 1\ A$, I is the discharge current, k is the Peukert coefficient (i.e., > 1 and typically 1.1–1.3), and t is the discharge time. Analytical models are obviously practical for a quick estimate, but they are not suitable for online electrical simulation.

Models based on a circuit equivalent, while less accurate than electro-chemical ones, solve the issue of usability in a simulation environment. Many embodiments of this type of models have been proposed, mainly characterized by (i) the underlying circuit netlist, and (ii) their time (i.e., continuous- vs. discrete-time) [6]. In this work we adopt the model template in Figure 2 [1], which is considered a sort of standard in the electronic design domain.

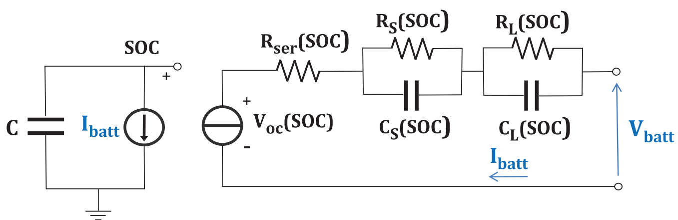


Fig. 2. The reference circuit equivalent template [1].

With respect to that of Figure 2, the circuit model in [1] actually includes a few more details regarding second-order effects such as self discharge, aging, and temperature dependence. Specifically, some circuit elements are parameterized also with respect to temperature and/or DOD. In this work, due to limited space, we focus solely on first-order effects related to the rated-capacity effect. This restriction does not however affect the validity of the methodology proposed.

The circuit consists of two main sections. The left section includes a capacitor C (modeling the nominal battery capacity) and a current generator modeling the load current I_{batt}. The voltage across the capacitor tracks the SOC of the battery (node SOC).

In the right branch of the model, a voltage-controlled voltage generator expresses the non-linear dependence of battery open-circuit voltage V_{oc} on SOC. The RC network models the battery impedance by exposing three components: the series resistance $R_{ser}(SOC)$ and two RC blocks tracking the short- (R_S, C_S) and long-term (R_L, C_L) time constants of the transients of the step response; all these parameters are generally function of the SOC.

C. Related work

Only few works have been proposed for modeling batteries from manufacturers' data. Although short term effects, or transient responses, are very important in most digital systems, they are not considered in [5] for lead-acid batteries, as well as in [2] for Li-ion cells. In [7], the author have considered a Thevenin-based circuit but only with a single transient for Li-ion batteries. More recently, the authors in [8] have generated both analytical and equivalent circuit models from datasheets; nevertheless, they do not truly validate the transient response.

III. Battery Datasheet Survey

Since our methodology is based on a data-driven paradigm, an essential preliminary step is the analysis of what information is provided by typical battery datasheets. To this purpose, we surveyed over 120 datasheets of batteries that included primary and secondary lithium-based and alkaline cells, and also valve-regulated lead-acid (VRLA) batteries.

TABLE I
Result of the battery datasheet survey.

Characteristic	Parameter	#	Battery Types			
			Li-based		VRLA	Alkaline
			P	S		
Voltage vs. time	Constant Current	1	13%	0%	5%	31%
	Constant Current	> 1	**79%**	8%	**68%**	**44%**
	Current pulse	1	9%	0%	0%	19%
	Current pulse	> 1	8%	5%	0%	19%
Voltage vs. SOC (or capacity)	Constant Current	1	6%	8%	0%	0%
	Constant Current	> 1	13%	**89%**	5%	6%
	Current pulse	1	4%	0%	0%	0%
	Current pulse	> 1	4%	0%	0%	0%
Internal resistance	text	-	19%	**54%**	**64%**	**38%**
	chart	≥1	19%	0%	9.1	6.3

Table I summarizes the results of our survey by reporting the percentage of datasheets that provide a given type of information. Since information is usually parameterized with respect to a quantity (e.g., load current in Figure 1), the column **Parameter** lists the type of parameterization, while the column **#** indicates the cardinality of the parameterization, i.e., whether the datasheets report one value or more (entries "> 1") values of that parameter. As will be seen below, this information has a significant impact on the selection of the model.

Besides being witness to the vast heterogeneity of the datasheet information, the table shows how different classes of battery tend to privilege different (and mostly disjointed) subsets of information. This is clearly visible by the numbers shown in bold. For instance, *voltage vs. time* characteristics are very popular for most batteries, but secondary lithium batteries tend to provide *voltage vs. capacity* curves (as those in Figure 1). Furthermore, many manufacturers provide the internal resistance, although this information is usually given under certain conditions of the battery (e.g., at full charge). However, only very few datasheets report the internal resistance value for different SOC conditions.

Although not exhaustive, this analysis clearly demonstrates our point: *having a fixed circuit template does not allow flexibility with respect to different battery types and chemistries*. As an example, in order to determine all the parameters of the template of Figure 2, *voltage vs. time* curves would be necessary for multiple current pulses (fourth row of the table). Regrettably, these curves are only available in about 5% of the surveyed datasheets for lithium-based secondary batteries, whereas building a model for a VRLA battery would simply be unfeasible: none of the products we analyzed provided the required information.

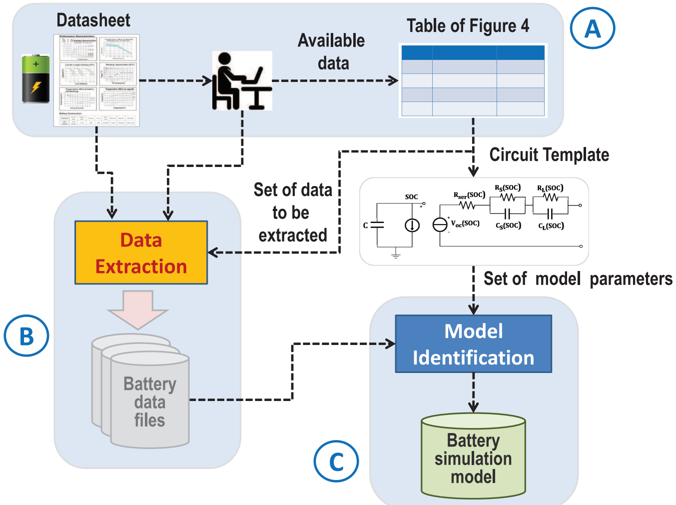


Fig. 3. Methodology flow

The model template must therefore be **composable**, consisting of modular "blocks" that can be added or removed based on the information available for the battery of interest.

IV. Overview of the Methodology

The proposed methodology is based on the flow depicted in Figure 3, which consists of three main phases:

- (A): **Template Selection**. The designer who wants to model a given battery checks the information in the battery's datasheet. On the basis on which, he/she selects the template to be used from Figure 4 based on the available data.
- (B): **Metadata Extraction**. Having chosen the model template, the designer tabulates the required information in *standardized formats*. This step implies manual intervention from the designer, who has to digitize the datasheet curves. Notice that the requirement of a standard format for the data files is the key for the automation of the following step.
- (C): **Model Identification**. Using the metadata files extracted in phase (B) and the model template from phase (A), a set of scripts calculates the parameters of the corresponding model. This step is fully automated and directly generates a simulatable model (currently a `.m` Matlab file).

The key element in the flow in Figure 3 is the table used in phase (A) that determines which model template is usable based on the data provided by the datasheet.

A. An Information-Driven Composable Model Template

Based on the typical datasheet information reported in Section III, we envisage four types of template (Figure 4), numbered 1 to 4, the fourth being the full template shown in Figure 2. The second column represents the type of information that makes it possible to build the model shown in the third column. It is worth emphasizing that the table considers the second column (the available data) as an index. The third column shows which circuit template is possible to build with the data in column two.

In our methodology, we assume that at least two quantities are always available for any battery: *the battery nominal voltage V_{nom} and the nominal capacity C_{nom}*. Even in the absence of a datasheet they are in fact always available (e.g., on the battery case). Unfortunately, when only these parameters are available, it is not possible to build any meaningful model other than an ideal generator (V_{nom}) and/or a capacitor C_{nom} representing the available energy. Clearly, this prevents modeling even the most basic non-idealities of a battery.

The following section explains the rationale for the entries in Figure 4.

1) Type 1 and Type 2 templates: If the datasheet provides a single battery *V vs. Capacity (or SOC)* curve, regarding a constant load current, it is possible to model only the rated-capacity effect through the relation described by this curve, i.e., a tabulated version of the voltage generator $V_{OC}(SOC)$ in the template.

When only a single reference current value is available, it is not possible to extract the sensitivity of voltage with respect to current, i.e., the battery resistance, unless the datasheet also provides a resistance value. In this case, a single *V vs. Capacity (or SOC)* curve **and** the resistance value lead to the selection of the Type 2 template (second bullet point in row *Type 2*).

If no resistance is provided, we need at least two *V vs. Capacity* curves at different discharge currents to choose a Type 2 template. Two of these curves (Figure 1) make it possible to calculate a ΔV by taking the difference between the two curves, and a $\Delta I = I_2 - I_1$ as the difference between the relative discharge currents I_1 and $I_2 > I_1$. By simply dividing by the two differences, we obtain a value of the internal resistance for different SOC values.

2) Type 3 and Type 4 templates: This sensitivity of battery characteristics to the dynamics of the load profile cannot be modeled through the *voltage vs. capacity* curves, since they refer to constant discharge currents. To that purpose, a *voltage discharge curve relative to a pulsed discharge current profile* is needed. A pulse makes it possible to determine the time constants in the voltage waveform associated to the discharge and rest period of the current pulse. Section V-A3 will describe how these time constants can be extracted.

V. Examples of Model Construction and Relative Validation

A. Identification of Model Parameters

The first parameter to be extracted for all four model templates should be the capacitance C: this is simply obtained by converting the nominal battery capacity C_{nom} (in Ah) into a capacitor of $C = 3600 \cdot C_{nom}/1V$ [F], where 1 Volt is the initial voltage across the capacitor that defines a fully charged battery [6].

1) **Type 1 Template:** In this case, the only remaining parameter is the $V_{OC}(SOC)$ generator. As already discussed in Section IV, this is simply derived by tabulating the *V vs. SOC/Capacity* curve.

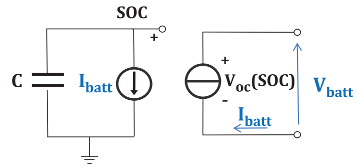
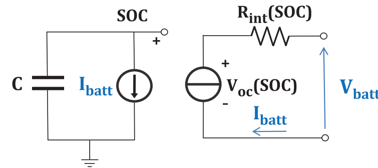
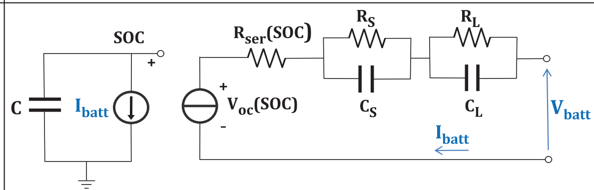
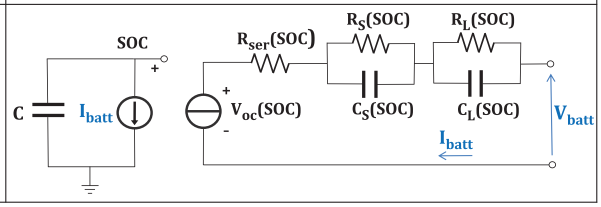
Type	Available Data	Circuit Template
1	• 1 V vs. Capacity (or SOC) curve	
2	• >1 V vs. Capacity curves at different currents **OR** • 1 V vs. Capacity curve + internal resistance	
3	As for Type2, plus: • 1 V vs. t curve for a current pulse	
4	As for Type 2, plus: • 1 V vs. t curve for a set of current pulses	

Fig. 4. Model templates table for first-order effects: based on what information are provided in the datasheet, the corresponding model template can be derived.

*2) **Type 2 Template:*** For this template, the voltage generator table is derived differently from Type 1. The Type 2 template also has the battery internal resistance $R_{int}(SOC)$ parameter. To extract these two quantities, we used the two *V vs. Capacity* curves in Figure 1 as follows. One curve (discharge current I_1) was fitted to yield a function $V_{batt}^{I_1}(SOC)$, whereas the other curve (discharge current I_2) yields a second function $V_{batt}^{I_2}(SOC)$.

The electrical parameters $V_{OC}(SOC)$ and $R_{int}(SOC)$ of the equivalent circuit are subsequently determined by solving the equations associated with the mesh on the right side of the Type 2 template [9], as follows:

$$\begin{cases} V_{OC}(SOC) = R_{int}(SOC) \cdot I_{batt}^{I_1} + V_{batt}^{I_1}(SOC) \\ V_{OC}(SOC) = R_{int}(SOC) \cdot I_{batt}^{I_2} + V_{batt}^{I_2}(SOC) \end{cases} \quad (1)$$

$$R_{int}(SOC) = \frac{V_{batt}^{I_1}(SOC) - V_{batt}^{I_2}(SOC)}{I_{batt}^{I_2} - I_{batt}^{I_1}} \quad (2)$$

Notice that there is a second combination of information in Figure 4 for Type 2. When the internal resistance is given by the datasheet, one *V vs. SOC* curve would suffice to achieve a Type 2 model. The only difference with the above analysis is that the resistance will be a constant and **not** a function of SOC, unless the datasheet provides that information.

*3) **Type 3 Template:*** In this case, $R_{int}(SOC)$ is the sum of all the resistances, so that for the extraction of the single RC elements, the procedure described in [10] can be adapted to the context. Consider the magnification of the voltage discharge curve shown in Figure 5: we can identify four regions.

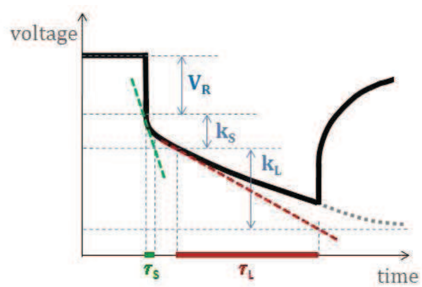


Fig. 5. Magnification of a voltage waveform in response to a current pulse and the characteristic elements required by Type 3/4 templates.

The first one is approximated by an instantaneous voltage drop $V_R = R_{ser} \cdot I_{batt}$, where R_{ser} denotes the series resistance and I_{batt} the value of the current in the pulse. The transient behavior starts from this point and consists of the superposition of two transient curves with different time constants. For the discharge phase $t_0 < t \leq t_d$, where t_0 and t_d are the start time and the total discharge time, respectively, the transient voltage is described by the following expression:

$$V_{transient}(t) = k_S \cdot \left(1 - e^{-(t-t_0)/\tau_S}\right) + k_L \cdot \left(1 - e^{-(t-t_0)/\tau_L}\right) \quad (3)$$

whereas for $t > t_d$ (i.e., during the relaxation time), it is given by:

$$V_{transient}(t) = k_S \cdot e^{-(t-t_d)/\tau_S} + k_L \cdot e^{-(t-t_d)/\tau_L} \quad (4)$$

where S and L denote short- and long-term contributions, respectively.

The voltage equation in the right mesh is then the following:

$$V_{batt}(t) = V_{OC} - R_{ser} \cdot I_{batt} - V_{transient}(t) \quad (5)$$

We derive k_S, k_L, τ_S, and τ_L by least-square fitting the available pulse waveform. These values make it possible to extract the model parameters as follows:

$$R_S = \frac{k_S}{I_{batt}};\quad C_S = \frac{\tau_S}{R_S};\quad R_L = \frac{k_L}{I_{batt}};\quad C_L = \frac{\tau_L}{R_L};$$

Since τ_L is much greater than τ_S, the transient effects can be considered in series, and not simultaneously, in order to simplify the extraction of the voltage drops k_S and k_L.

The fourth region in fig. 5 refers to the relaxation time after the current pulse returns to zero.

4) **Type 4 Template:** In order to incorporate SOC dependence into the RC groups we simply need to repeat the above procedure for a second pulse. The second run will yield a different set of values of R_S, C_S, R_L, C_L, which can be transformed into a function of the SOC by linear interpolation. Obviously, if multiple pulses are available in a datasheet, we can use multiple runs of the model construction and derive a more accurate interpolation to derive the dependence of R_S, C_S, R_L, C_L on the SOC.

B. Validation of the Models

Herein we demonstrate the proposed methodology on two battery cells, namely, a Panasonic NCR18650E Li-ion rechargeable cell [11], and a Renata CR2032 Li/MnO_2 primary cell [12].

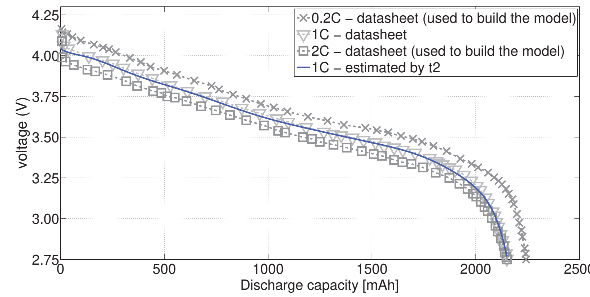
The datasheet of the NCR18650E cell provides various *V vs. discharge capacity* curves, which allow us to validate model Type 2. We used the two curves for currents 0.2C and 2C (C-rate is the current rate normalized to the nominal capacity of the battery) to derive the model as described in Section V-A2. Once the model was built, we applied a constant load of 1C and compared the resulting estimated characteristic to the datasheet curve for the 1C load.

Figure 6(a) shows that the model accuracy is excellent: the blue curve almost perfectly overlaps with the original curve (triangle markers).

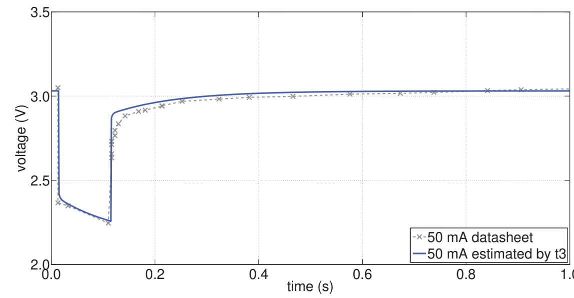
The Renata CR2032 is one rare example of a battery for which the manufacturer also provides pulse discharge characteristics for various currents (specifically, 10, 20, 50 and 100 mA) through *V vs. time* plots, which allow us to identify the parameters of model Type 3. We used the data at 20 mA and 100 mA to derive the parameters as described in Section V-A3, and the 50 mA was used for testing it. Figure 6(b) shows the response of the model to the 50 mA pulse (solid curve) against the digitized version of the original data given by the manufacturer. Again, the fit is quite good.

C. Automation Issues

Although the first steps of modeling, for data extraction and collection, need a mostly manual process by the designer, on the other hand, selection and generation of the battery model with its related parameters can be automated. For instance, standardization of data structures and file names makes it possible to read them easily by a tool, which could select automatically the best template after considering all the files (i.e., data types) available for a certain battery. Then, the battery model can be described in a hardware design language like SystemC, or in SPICE code for the circuit simulation.



(a)



(b)

Fig. 6. Validation of Model Type 2 for Panasonic NCR-18650E (a) and validation of Model Type 3 for Renata CR2032 (b).

VI. Conclusions

Battery modeling has become fundamental in designing electronic systems. In this paper we proposed a methodology that is able to build different equivalent circuit models through composable templates, starting from the available data provided by the manufacturer. In this way, even datasheets with only minimal amounts of data make it possible to build a circuit equivalent, albeit simpler.

Validation was performed by modeling two different lithium-based batteries: Panasonic NCR18650E rechargeable cell and Renata CR2032 primary cell. Results demonstrate that the proposed methodology is always able to generate a battery model with an accuracy which is dependent on the amount of information available from the battery manufacturers.

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